GaN-on-Diamond with Ultra-Low Thermal Barrier Resistance

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Abstract: *We investigated the effective thermal boundary resistance (TBR_{eff}) of GaN-on-Diamond interfaces for diamond growth with a ~ 5nm SiNx, a ~ 5nm AlN interfacial layer, or without any interfacial layers, respectively. It was found that the SiNx interfacial layers resulted in smooth and sharp interfaces, but direct growth of diamond on GaN exhibited very rough interfaces. TBR_{eff} is strongly correlated with interface quality. With a ~ 5nm SiNx interfacial layer, a TBR_{eff} as low as 2.5 m^2k/GW was achieved, which is more than five times better than the previously reported best data, and close to the limit predicted by theoretical models for GaN-diamond interfaces*

Keywords: GaN-on-Diamond; ultra-low thermal boundary resistance; TBR_{eff}, interfacial layers; high density dielectric

Introduction

While GaN-based RF transistors, typically on SiC substrates, offer impressive power densities across a wide range of frequency bands, leveraging the superior material properties, their full potential is yet to be realized, mainly due to thermal limitations. Diamond, which offers superior thermal conductivity of ~ 2000 W/mK, is a natural choice for GaN HEMTs for heat dissipation. By using a diamond substrate, significant improvement of the GaN transistor's power density can be achieved with the same transistor area, by improving the heat dissipation. Promising GaN on diamond results have been demonstrated previously[1,2]. However, the thermal resistance at the interface between GaN and diamond is the bottle neck for ultimate heat dissipation. Such thermal resistance at the GaN - diamond interface is primarily due to the use of a low thermal conductivity nucleation layer during diamond growth, or a dielectric material for diamond wafer bonding. The interfacial thermal resistance can contribute significantly to the total device thermal resistance and must be minimized to gain the maximum benefit from GaN-on-Diamond technology. In this study, we focused on minimizing such interfacial thermal resistance by optimizing structure design and the initiation of the diamond growth. We demonstrate an effective thermal boundary resistance (TBR_{eff}) as low as 2.5 m^2k/GW, which is a >5X reduction from the current state-of-the-art (SoA) results[3].

GaN-on-Diamond preparation and surface morphology

To deposit diamond on GaN by the CVD method, a relatively low-thermal-conductivity interfacial layer is typically deposited to improve the nucleation and adhesion of the diamond film. Obviously, the contributions of such interfacial layers to the total thermal resistance are determined by its thermal conductivity and its thickness. In addition, the physics of phonon transfer near the diamond nucleation interface must also be considered, which implies that a smooth rather than rough interface may be preferred for the reduction of phonon scattering at the interface. Therefore, a reduced thickness interfacial layer with smooth interfacial roughness could be key to reducing TBR_{eff} and pushing it towards theoretical limitations, given the reduced thickness interfacial layer is adequate for enabling the subsequent diamond growth. Furthermore, completely eliminating such an interfacial layer would be desirable. For example, diamond could be directly deposited on GaN. However, if the resulting interface is very rough and enhances the phonon scattering at the interface significantly, the thermal resistance may be limited by roughness itself relative to the use of an interfacial layer. We compared three different GaN-Diamond interfaces to optimize the interfacial layer for diamond growth on GaN to achieve the lowest TBR_{eff}: with ultra-thin (~5nm) high density SiNx transition layer, with (~ 5nm) AlN transition layer, and without any interfacial layer (diamond directly on GaN). The diamond films were grown by a microwave plasma CVD system which is able to handle diamond growth of up to 50mm wafer scale at Fraunhofer USA Center for Coatings and Diamond. Similar reactors with up to 100mm wafer scale capability are also available. Diamond nucleation was performed prior to the CVD Diamond growth. During each diamond growth run, 3 different samples (with SiNx interfacial layer, with AlN interfacial layer and without any interfacial layer) were loaded together so that we can purely study the impact of interfacial layer on the diamond growth, eliminating any variation from run to run. Successful diamond growth was achieved on all wafers regardless of using a transition layer or not. As showed in Figure 1, similar surface morphologies were observed for the three different interfaces for ~ 8.5 µm thick films. The average grain size of the diamond on the SiNx transition layer seemed to be slightly smaller than other two, but overall the grain size of all the diamond films are similar when compared to each other as well as comparing to the previously reported works.

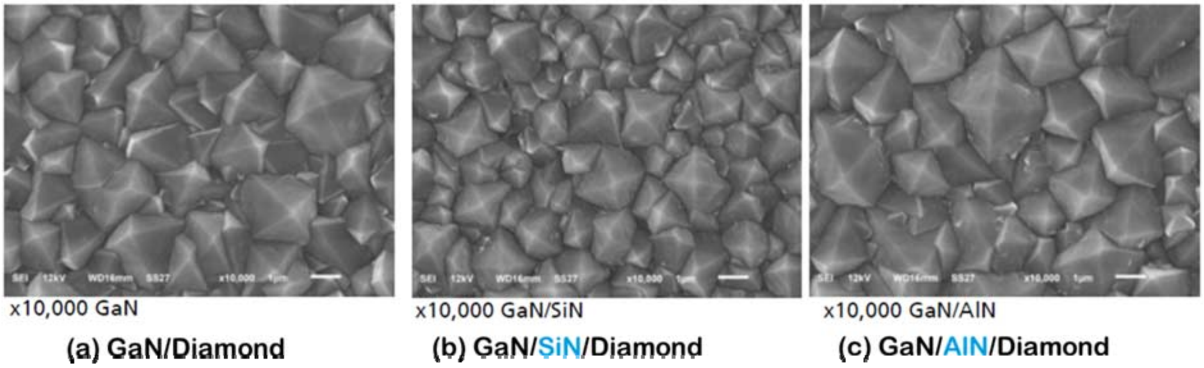


Figure 1. Surface morphology of ~ 8.5 μm diamond on GaN with three different interfaces (a) no interfacial layer, (b) with SiNx layer, and (c) with AlN layer

Thermal characterizations

The TBR_{eff} characterization and analysis was performed at the University of Bristol, using a contactless thermal boundary resistance measurement method similar to as reported in Ref.[4] Results are summarized in Figure 2, shown together with the SoA results previously published[3]. Interestingly, at first glance the sample with diamond grown directly on GaN, without any interfacial layer, showed the highest TBR_{eff}, and the sample with the ~ 5nm SiNx transition layer had the lowest TBR_{eff}. More specifically, the direct diamond growth on GaN sample, without interfacial layer, has the highest and widest spread of TBR_{eff} (65~85 m^2k/GW) across the wafer studied. In contrast, both GaN-Diamond samples using either 5nm SiNx or AlN interfacial layers showed very low TBR_{eff}. Samples using an AlN interfacial layer have a TBR_{eff} between 10~18 m^2k/GW, which also compares favorably with SoA results, but the TBR_{eff} distribution is relatively large. Lastly, samples using the SiNx interfacial layer have a TBR_{eff} as low as 2.5 m^2k/GW, which is approaching the diffuse mismatch model (DMM) theoretical limit ie the theoretical limit what is possible for GaN-diamond interfaces. Moreover, the distribution of the TBR_{eff} over the sample surface using SiNx interfacial layer is fairly tight. The blue bar (SiNx) shown in Figure 2.(a) includes more than 20 data points from different regions of the GaN on Diamond samples and different diamond growth conditions, implying the diamond growth on GaN using the SiNx interfacial layer is uniform.

The thermal conductivity of the diamond itself was extracted from the transient reflectance data and is plotted in Figure 2(b). The impact of the diamond growth chemistry has been studied in a set of controlled samples, which are plotted together with literature data for comparison. It needs to be pointed out that the thermal conductivity extracted for the diamond at this stage corresponds to a combined value between the in-plane and cross-plane values. The thermal conductivity of the thin diamond layers can be increased through the CH_4 ratio in the chamber by a factor of ~3 by decreasing the CH_4 from 1% to 0.3%, as shown in Figure 2(b). In general, the thermal conductivity values of the diamond measured here, especially those grown under a lower CH_4 concentration (0.3%), compares well with other diamond samples measured at the University of Bristol using Raman thermography and transient thermoreflectance. It is also noticed that the growth temperature has a large impact on the diamond conductivity as well, and further studies of growing diamond at elevated temperature as well as using CH_4 concentration lower that 0.3% are under way.

TEM characterizations

Since the dramatic difference in the TBR_{eff} (Figure 2a) could not be simply explained by the small difference in surface morphology as showed in Figure. 1, to further understand the difference in TBR_{eff} for the three samples, we performed TEM analysis to compare the interfacial quality and the results are showed in Figure 3. It is clear that the three samples have dramatically different interface morphologies, and such differences are strongly correlated with the measured TBR_{eff}. The sample using the SiNx interfacial layer showed a very uniform and smooth interface (Figure 3b). The sample using the AlN interfacial layer show a slightly rough interface (Figure 3c). Diamond directly grown on GaN, without any interfacial layer, (Figure 3a) exhibited a rather rough interface. When a SiNx or AlN layer was not used, severe jaggedness at the interface was observed, which is likely due to the reaction between GaN and the growth environment used to initiate the diamond nucleation. Typical diamond CVD growth was initiated in a hydrogen containing plasma at elevated temperature. It is well known that GaN can be etched by hydrogen at high temperatures, and AlN has better thermal stability under similar conditions. Therefore, the sample with the AlN interfacial layer has a better interface, compared to direct growth on GaN. Another interesting observation of the samples using the AlN interfacial layer is that we observed many AlN "terrace" features (Figure 3c), and additional examples are shown in Figure 4(a). These terraces are believed to be formed during the AlN interfacial layer preparation and can at least partially explain the relatively larger TBR_{eff} distribution as seen in Figure 2(a).

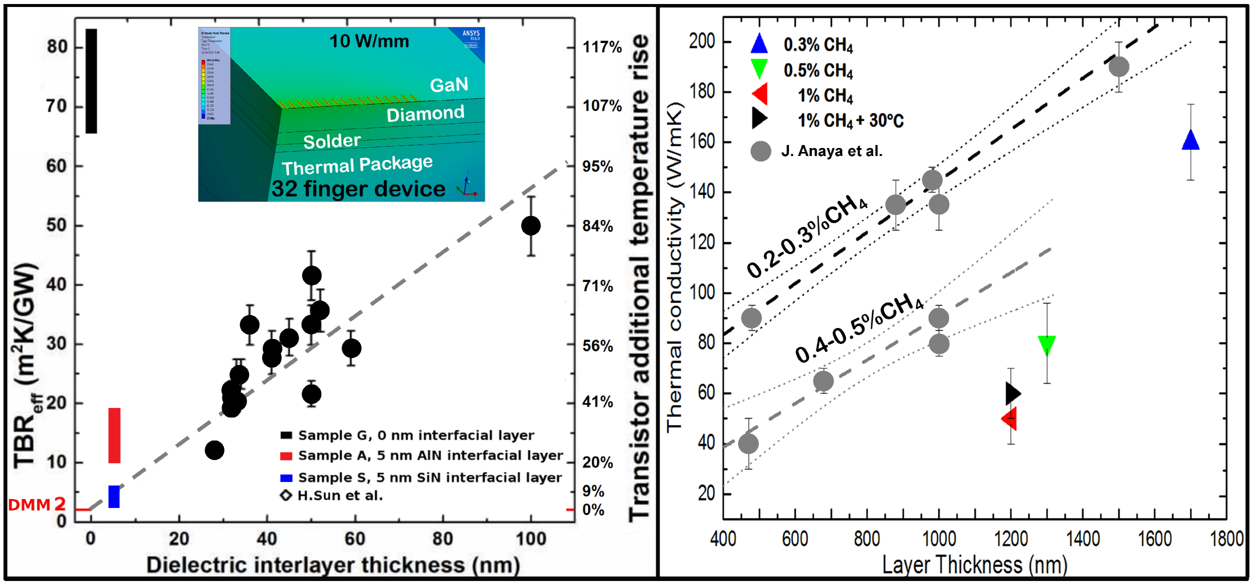
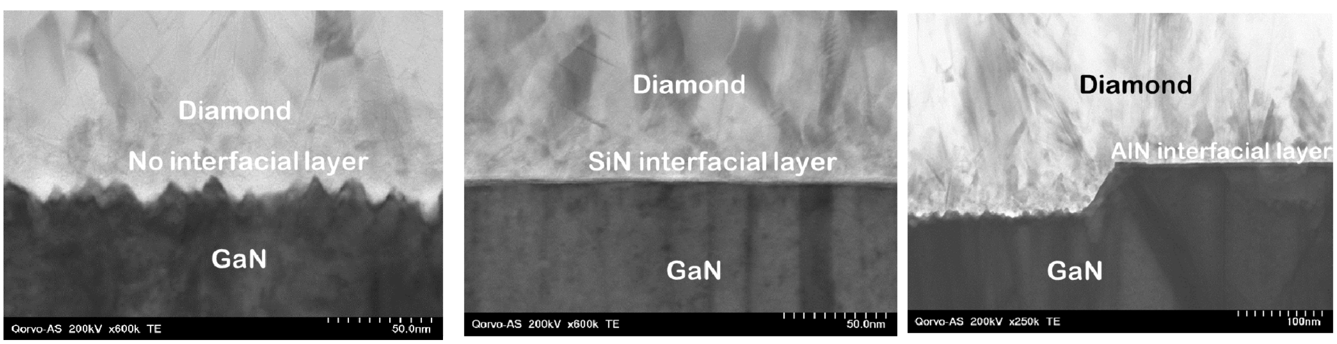
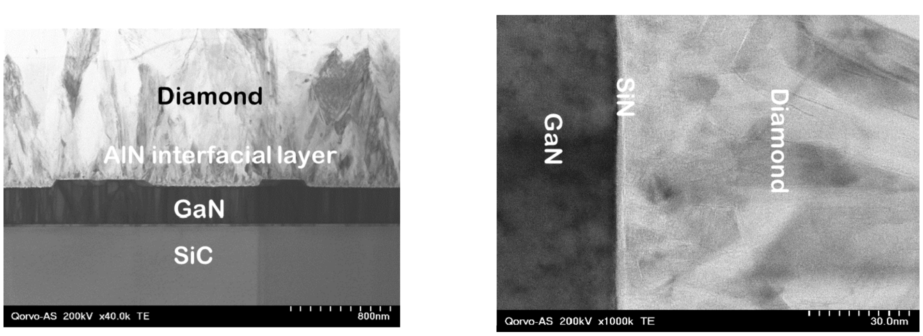


Figure 2. (a) left side, Measured TBR_{eff} characterization for three different interfaces. Literature data from Ref. [3] are also included for comparison. (b) right side, extracted thermal conductivity of initial diamond growth (<2μm thick). Literature data from Ref [5] are also included for comparison.



(a) GaN/Diamond **(b) GaN/SiN/Diamond** **(c) GaN/AlN/Diamond**

Figure 3. (a) Cross sectional TEM comparison for three different interfaces, (a) diamond directly on GaN, (b) with SiNx interfacial layer, and (c) with AlN interfacial layer.



(a) Diamond/AlN/GaN shows multiple AlN terraces

(b) Diamond/SiN/GaN. The SiN thickness is around 4~5nm

Figure 4. (a) Cross sectional TEM shows AlN terraces (b) Cross sectional TEM shows SiNx thickness around 4~5nm.

The high density SiNx layer, appears to survive the diamond nucleation process, and therefore protects the GaN surface from etching. The thickness of the SiNx layer is confirmed to be around 4~5 nm, as shown in Figure 4(b) in the zoomed-in TEM image. The SiN layer looks very uniform, with no evidence of etching or decomposition during the diamond growth. This correlates well with the ultra-low and very tightly distributed TBR_{eff} results as we discussed in Figure 2(a).

As we discussed previously, an interfacial layer with low thermal conductivity is not the most desirable option, but the control of interfacial roughness is also a key factor to minimization of the TBR_{eff}. The thermal resistance of SiNx is believed to be higher than AlN, and it is obviously higher than the case when an interfacial layer is not used, yet the diamond growth on GaN using high density SiNx generates the lowest reported TBR_{eff}. This is in part due to the fact that we were able to limit the SiNx thickness to 5nm or less. It will be interesting to further optimize the diamond nucleation conditions to avoid roughening the interface for direct growth on a GaN surface and to evaluate if further improvement of TBR_{eff} can be realized.

Summary

We have demonstrated an ultra-low thermal barrier resistance for diamond grown on GaN with a ~ 5nm high quality SiNx interfacial layer. The measured TBR_{eff} ~ 2.5 m^2k/GW establishes a new record for GaN on diamond. The reduced thermal barrier resistance is due to the thinness of the SiNx layer and maintaining a smooth and uniform interface. The present result approaches the diffusion mismatch theoretical limit. In contrast, the direct growth of diamond on GaN had a much higher thermal barrier resistance due to the extremely rough interface, and indicates that phonon scattering at the interface is a very important factor for minimizing the TBR_{eff}. Therefore, optimization of the interface to enhance the phonon transportation at the interface, will be a focus in future research. Nevertheless, our current approach (GaN on Diamond with an ultra-thin, high density SiNx interfacial layer) is a highly promising thermal management solution for enabling high RF power density and efficiency for GaN MMICs.

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